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System development and self-sustainability analysis for upgrading human waste to power

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ABSTRACT

This paper presents a system to upgrade faecal matter in an environmentally friendly way by the deployment of plasma gasification and SOFC (solid oxide fuel cells). The entire system chain, including a dryer, a microwave-assisted plasma gasifier, a gas processing system and an SOFC system, is studied to evaluate system performance and self-sustainability. The effects of gas processing approach, moisture content and oxidant-to-fuel ratio on system self-sustainability are studied in detail. The results show that the variables aforementioned strongly affect system performance. It is recommended to deploy the approach of adding air, a mild moisture content (30% by weight) and an intermediate oxidant to fuel ratio (1.05 kg kg^{-1}) to achieve enhanced system performance under the conditions studied.

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1. Introduction

Sustainable development requires an efficient and environmentally friendly management of wastes. Conventional routes available for waste management are combustion, pyrolysis and gasification. Among these routes, gasification serves as a valuable process that transforms low value feedstock into valuable products and fuels. Unlike conventional gasification power plants, plasma gasification offers complete gasification even at a small scale due to the elevated operating temperature. Therefore, plasma gasification is considered as an environmentally sustainable technology for waste treatment. It is well known that fuel cells, particularly SOFCs (solid oxide fuel cells) possess an enhanced fuel-to-electricity efficiency due to the direct conversion of chemical energy to electricity, and SOFCs can potentially use multiple fuels including syngas from plasma gasification. Thus, power plants based on plasma gasifiers and SOFCs are likely to be highly efficient in upgrading wastes to green electricity.

Compared to conventional biomass gasification technology such as air-blown down-draft fixed-bed gasifiers, plasma gasification technology is still at an early developing stage. Conventionally, plasmatron uses an electric arc which is formed by applying a high potential difference to two electrodes to ionize the passing gas and to generate a high temperature that is particularly effective for the gasification of various fuels. By contrast, an innovative approach to generate plasma is using microwaves, which is less energy-intensive, more economic viable and relatively more efficient [3]. Depending on the design, the conversion efficiency of electricity-to-microwave can be as high as 100% [4]. Both kinds of plasmatrons have been applied and studied in experiments; for example, Ray et al. [5] presented an advanced gasification technology that combines a fluidized bed gasifier and a plasma gasifier enabling to treat various wastes, and reported a high carbon and energy conversion efficiency. Yoon and Lee [6] studied the variation in the syngas composition and the microwave-driven plasma gasification efficiency when various plasma gases and feedstock were used. Particularly, they looked into the effects of oxygen-to-fuel ratio on the syngas composition and the gasification efficiency. Hong et al. [1] employed 2.45 GHz microwave energy for coal plasma gasification in oxygen/air plasma and steam/air plasma. With the oxygen/air plasma, further increasing coal flow rate above 2.0 kg h^{-1} does not significantly affect the syngas concentration, whereas with the steam/air plasma, the syngas concentration becomes relatively stable when the mass ratio between coal and steam is above 0.45 (kg kg^{-1}). The authors also suggest SOFCs coupled with plasma gasification would be interesting for highly efficient power generation in the future. Wang et al. [2] studied the effects of microwave power, processing time, water content and biomass size on microwave torrefaction of rice husk and sugarcane. The results suggest that microwave power of the order of 250–300 W favors the syngas production with a relatively fine biomass size. They

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Nomenclature

E	energy, kW
E_x	exergy, kW
F	Faraday constant, C mol^{-1}
I	current density, mA cm^{-2}
M	molecular weight, kg mol^{-1}
P	pressure, Pa
R	the universal gas constant, J mol^{-1} K^{-1}
R_{eq}	equivalent resistance, Ω cm^2
T	temperature, K
U_F	fuel utilization, %
$V_{rev,x}$	reversible cell voltage, V
Y_i	molar fraction of species, i

Greek letters

η	efficiency, %
Φ	flow rate, kg s^{-1}

Superscripts and subscripts

an	anode
aux	auxiliary
ele	electricity
in	inlet
out	outlet

Abbreviations

AC	alternating current
AP	auxiliary power, kW
APD	air preheating duty, kW
CHP	combined heat and power
CPOX	catalytic partial oxidation
DC	direct current
EFP	electricity for plasmatron, kW
FCP	fuel cell power, kW
FPD	fuel preheating duty, kW
GDC	gadolinia doped ceria
HHV	higher heating value, kJ kg^{-1}
LHV	lower heating value, kJ kg^{-1}
LSM	lanthanum strontium manganese oxide
NE	net electricity, kW
NEE	net electrical efficiency, %
OTFR	oxidant-to-fuel ratio
SOFC	solid oxide fuel cell
YSZ	yttria stabilized zirconia

conclude that microwave-induced torrefaction enhances the caloric value, increases the carbon content, and decreases the oxygen content of torrefied solid products efficiently and economically in comparison with conventional torrefaction.

Literature survey shows that current efforts mainly focus on plasma gasification, and studies on the system development based on plasma gasification and SOFCs are very limited. This work attempts to fill this gap and to achieve suitable operating regime for the development of such a power plant. Detailed studies on system self-sustainability under various operating patterns are analyzed.

2. System layout

The system layout is shown in Fig. 1 which includes fuel pretreatment, a dryer, a plasma-assisted gasifier, a gas cleaning and processing system and an SOFC system. The electricity generated from the SOFC system is expected to overcome the power consumed by the microwave generator and other auxiliary components like blowers and pumps, whereas heat generated by combustion using unreacted electrode off-gas in the SOFC system is utilized for drying, fuel and air preheating, and/or steam generation.

2.1. Fuel pretreatment

Human faecal matter is selected as the fuel for the plasma gasification. The pre-dried matter contains high moisture content (70–80% by weight) and requires being reduced to a certain range for the operation of the plasma furnace. In addition to the water reduction, depending on the design of the feeding, the faecal matter may need to be milled before feeding it into the furnace.

2.2. Plasma gasification

The plasma gasification system studied includes a microwave generator with 2.45 GHz frequency, air and fuel feeding and control parts, a reactor as well as temperature, gas composition and tar measuring/analysis equipment. A schematic drawing of the plasma setup is shown in Fig. 2.

As analyzed by Rutberg et al. [8], the use of air as plasma gas is relatively simple and promising for the development of plasma gasification technology. Therefore, in this work air is the plasma gas in the studies.

2.3. Gas cleaning and gas processing

Plasma gasification inevitably generates a certain amount of trace species which, without proper cleaning, may degrade SOFC performance. The type and the amount of the trace species can vary substantially depending upon the fuel types and operating conditions applied. In this study, a gas cleaning system is being developed to deal with the potential trace species, including particulates, alkali compounds, heavy metals, acid gases (HCl and H_2S) and tars. This preliminarily design shown in Fig. 3 is believed to result in

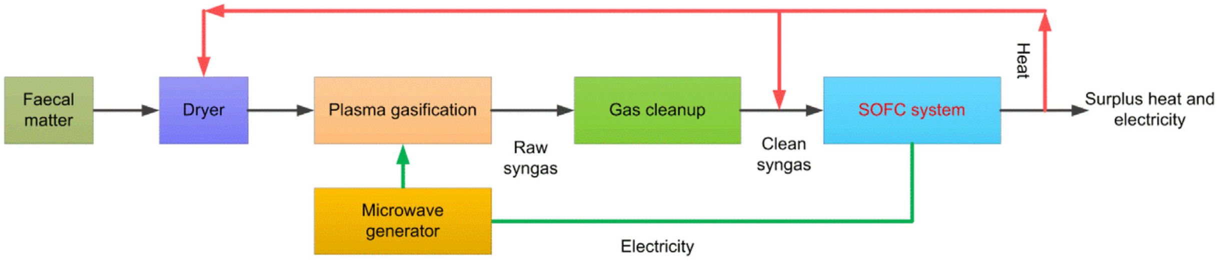

Fig. 1. The main flow scheme of the integrated plasma gasifier–SOFC system.

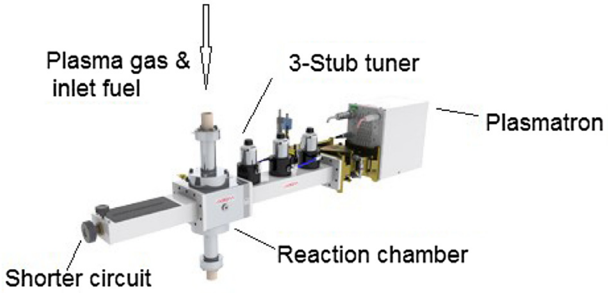

Fig. 2. A schematic view of the plasma furnace (adopted and redrawn from Ref. [7]).

sufficiently clean syngas for SOFC applications based on previous studies [9,10]. A cyclone which is already a part of the plasma gasification system primarily removes large particulates. Scrubbers including a spray scrubber and a venturi scrubber are applied to remove the major content of the trace species. Following the scrubbers, sorbent-based units are connected to capture the compounds such as H_2S which might escape from the scrubbers. A ceramic filter is installed at the final stage to capture any particles that escape from the previous treatments. In this way, a clean-enough syngas can be obtained and is fed to the downstream SOFC system.

After the gas cleaning, the syngas obtained possesses a relatively low temperature (approximately 400 °C) and requires being heated up before entering the SOFC. As explained by Aravind et al. [11], heating up or cooling down syngas may encounter the risk of carbon deposition, which is likely to be avoided by adding air/oxygen and/or steam.

2.4. SOFC system

Electrolyte-supported fuel cells which form the SOFC stack comprises of an electrolyte on which the electrodes are applied. The anode is made from NiO/GDC material and the cathode is manufactured from LSM (lanthanum strontium manganese oxide) perovskite material. The thickness of both electrodes and of the TZ3Y electrolyte are 40 and 100 μm, respectively. Various fuels can be used and air performs both as an oxidant and coolant for the stack.

The layout of the SOFC system developed is illustrated in Fig. 4. It includes two heat exchangers which are used for preheating the fresh syngas to approximately 700 °C and air to 600–650 °C. After the preheating, the fuel and air enter the stack which works at approximately 800 °C. The stack off-gases flow to a burner, from which the flue gas is used for the preheatings aforementioned. The flue gas exhausted after the preheating is further used to dry the faecal matter and/or for hot water production.

3. Modeling

Integration of the described subsystems results in a complete power plant that is built and simulated in Cycle-tempo [12] to evaluate system performance. Cycle-tempo employs a Gibbs free energy minimization method to design, analyze, optimize and monitor the thermodynamic behaviors of an energy system. It includes an extensive and validated model library for both conventional and innovative components such as fuel cells, and carries out energy and exergy analysis for the entire power plant comprised of the available components. Readers are referred to the program manual [12] for more details. The entire flow scheme of the power plant is illustrated in Fig. 5 and the modeling approach is further explained in the following sections.

3.1. Plasma gasification

Thermodynamic equilibrium can hardly take place in a gasification process that possesses a temperature lower than 800 °C. However, at elevated temperatures (>800 °C), it seems reasonable to assume an equilibrium condition. Such an assumption is commonly adopted in modeling plasma gasification and is proven by the experimental data [5,13]. The plasma gasification studied is simulated through the standard gasifier module that employs Gibbs energy minimization in the cycle-tempo library. As seen in Fig. 5, faecal matter (No.1) together with air (No.2) is gasified in a plasma furnace (No.4) using the microwave generated from a plasmatron (No.6). The raw syngas generated is delivered via pipe No. 7 to a gas processing system.

3.2. Gas processing and drying

Considering the maturity of the relevant gas cleaning technology for each trace species and system operational reliability, we designed a gas cleaning system which is a combination of high-temperature and low-temperature gas cleaning technology. In the simulations, gas cleaning processes like kinetics, mechanisms are not actually modeled; instead, the changes of thermodynamic parameters such as temperature and pressure are implemented. As discussed the raw syngas is first conditioned by a scrubber (No.9) and is then preheated to approximately 400 °C for H_2S and HCl removal, represented by a reactor (No.17). A certain amount of air is added to the main stream before feeding into an SOFC stack (No.16) via pipe No.22.

The drying process is simulated by the calculation of the amount of heat required to reduce the moisture content to a desired condition. Specifically, the heat available in pipe No. 27 is used to evaporate the water delivered by pipe No.28 in Fig. 5.

3.3. SOFC modeling

The SOFC model first takes the inlet gas to the equilibrium conditions at the operating temperature. Then, the current flow I (Eq. (1)), the cell voltage V (Eq. (5)), and the electrical output power P_e (Eq. (6)) are calculated. It is assumed that the processes occur at a constant temperature and pressure. Gas compositions are also assumed to be constant in the cross section, perpendicular to the direction of the fuel cell flow. A set of equations are used in the fuel cell model which are given below.

$$I = 2F\frac{U_F\Phi_{m,an,in}}{M_a}\times\left(y^0_{H_2}+y^0_{co}+4y^0_{CH_4}\right) \tag{1}$$

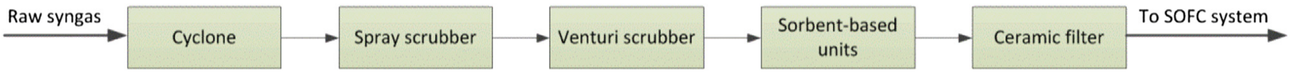

Fig. 3. The gas cleaning system developed.

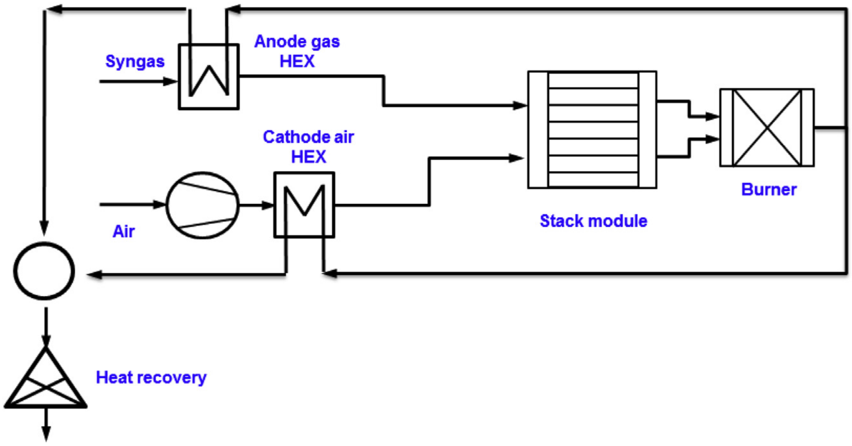

Fig. 4. The flow scheme of the SOFC system.

$$V_{rev,x} = V^0_{rev} + \frac{RT}{2F}\ln\left(\frac{y^{1/2}_{O2,c}y_{H_2,an}}{y_{H_2O,a}} \times p^{1/2}_{cell}\right) \quad (2)$$

$$i_x = \frac{I}{A} \quad (3)$$

$$\Delta V_x = i_x \times R_{eq} \quad (4)$$

$$V = V_{rev,x} - \Delta V_x \quad (5)$$

$$P_e = V \times I \times \eta_{DC/AC} \quad (6)$$

where $\Phi_{m,an,in}$ is the mass flow rate of fuel that enters the anode (kg s^{-1}), y^0_i are the concentrations at the anode inlet (i represents H_2,CO and CH_4), M_{an} is the molecular weight of the anode gas (kg mol^{-1}), F is the Faraday constant (C mol^{-1}), U_F is the fuel utilization, $V_{rev,x}$ is the reversible voltage (V), V^0_{rev} is the standard reversible voltage for hydrogen (V), i_x is the current density (mA cm^{-2}), R_{eq} is the equivalent resistance (Ω cm^2), ΔV_x is the voltage loss (V), T is the working temperature of the fuel cell stack (K), R is the universal gas constant (J mol^{-1} K^{-1}), p_{cell} is the operating pressure of the fuel cell stack (Pa), and $\eta_{DC/AC}$ is the efficiency of the DC/AC inverter.

The unused fuel and air are further reacted in a combustor (No.19), generating heat (Eqs. (7) and (8)) for preheating the incoming air via pipe No.24 and fuel via pipe 11 using heat

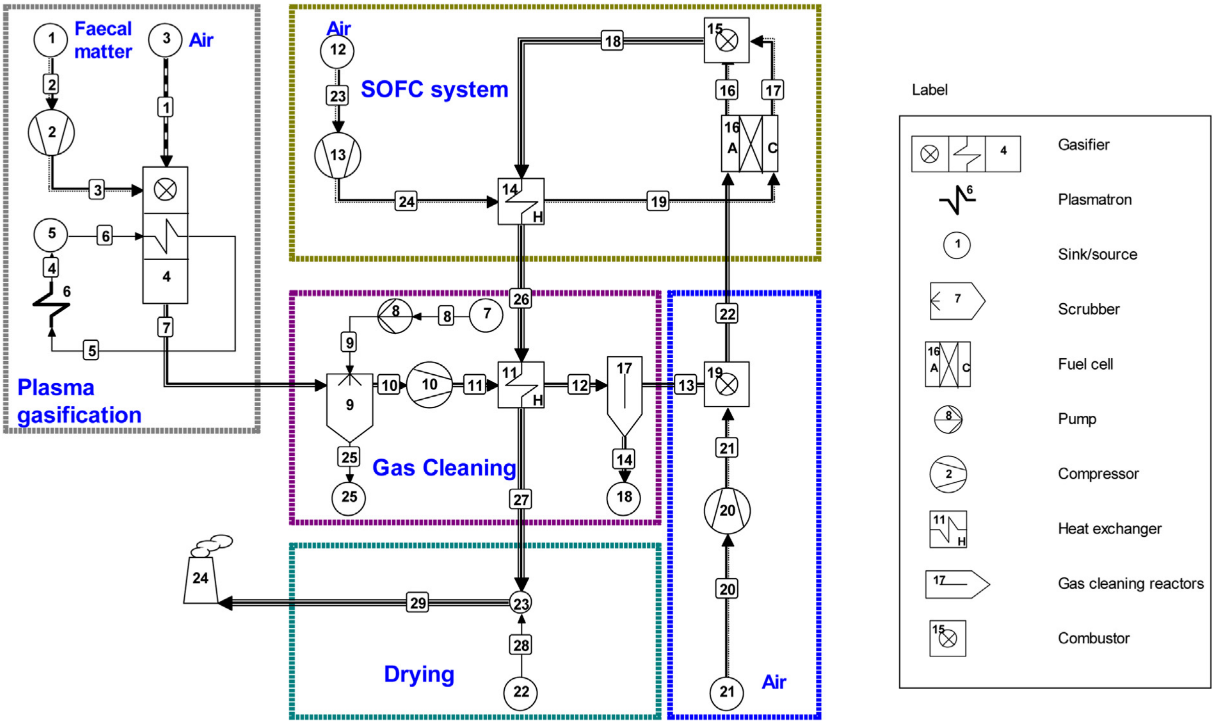

Fig. 5. The main components and system layout in Cycle-tempo with air addition.

exchangers No.14 and No.17. The gas exhausted is emitted to a flue gas stack (No.24) via pipe No.29.

$$H_2 + O_2 \rightarrow H_2O \quad \Delta H^0 = -283 \text{ kJ mol}^{-1} \tag{7}$$

$$CO + O_2 \rightarrow CO_2 \quad \Delta H^0 = -286 \text{ kJ mol}^{-1} \tag{8}$$

3.4. Energy and exergy efficiency

Thermomechanical exergy and chemical exergy are calculated with a reference environment, which is set at a temperature of 25 °C and a pressure of 101,325 Pa with an air composition of Ar 0.91%, CO_2 0.03%, H_2O 1.68%, N_2 76.78%, O_2 20.60%.

The net electrical efficiency (biomass to electricity, %) is defined as

$$\eta_{E_{\text{ele}}} = \frac{E_{\text{ele\_out}} - E_{\text{ele\_in}} - E_{\text{aux}}}{M_{\text{biomass fuel}} \times \text{LHV}_{\text{biomass fuel}}} \tag{9}$$

where $E_{\text{ele\_out}}$ is the electricity generated by the SOFC system (kW), $E_{\text{ele\_in}}$ is the electricity consumed by the plasmatron (kW), E_{aux} is the total power consumption of auxiliary components, including compressors and pumps (kW), $M_{\text{biomass fuel}}$ is the mass flow of the biomass fuel fed to the system (kg s^{-1}), $\text{LHV}_{\text{biomass fuel}}$ is the LHV (low heating value) of the biomass fuel (kJ kg^{-1}). Likewise, the heat efficiency can be defined. The total CHP (combined heat and power) efficiency (%) is gained by adding the efficiencies of electricity and heat.

Exergy efficiency is defined as the ratio between the exergy of the products and the fuel input exergy. The net electricity exergy is given by Eq. (10) and the heat exergy efficiency is described by Eq. (11). The system overall exergy efficiency is the sum of heat and net electricity exergy efficiencies, and is described by Eq. (12).

$$\eta_{E_{\text{x,ele}}} = \frac{E_{\text{x,ele}} - E_{\text{x,aux}}}{M_{\text{biomass fuel}} \times E_{\text{x,biomass fuel}}} \tag{10}$$

$$\eta_{E_{\text{x,heat}}} = \frac{E_{\text{x,heat}}}{M_{\text{biomass fuel}} \times E_{\text{x,biomass fuel}}} \tag{11}$$

$$\eta_{E_{\text{x,CHP}}} = \frac{E_{\text{x,heat}} + E_{\text{x,ele}} - E_{\text{x,aux}}}{M_{\text{biomass fuel}} \times E_{\text{x,biomass fuel}}} \tag{12}$$

where $E_{\text{x,a}}$ is the total exergy losses caused by the auxiliary components (kJ kg^{-1}), $E_{\text{x,biomass fuel}}$ is the exergy of the biomass fuel fed to the system (kJ kg^{-1}).

Assumptions made for the simulations are: (1) the power plant operates at steady-state; (2) pre-dried faecal matter possesses a moisture content of 80% by weight; (3) faecal matter with a certain moisture content (by weight) and a known composition are used for the calculations; (4) air is the plasma gas for the gasification process; (5) electricity to microwave power has an efficiency of 92%; (6) the oxidant ratio for the gasification process is slightly lower than conventional gasification processes; (7) heat losses in the plasma gasification process, during the gas delivery and in the SOFC system are ignored. The inputs for the simulations are summarized in Table 1.

4. Model validation

The plasma gasifier and the SOFC system are the two most critical components in the entire energy chain. Therefore, these two models need to be confirmed experimentally. The SOFC model used has been compared with experimental data in our previous paper [15], and therefore it is not further addressed. The gasification model developed for conventional biomass gasifiers operating at 800 °C has also been validated in our previous studies [11,15] and is in a reasonable agreement with the experimental data. For plasma gasification, we used an experimental condition from the work of Rutberg et al. [8] and gain comparable results given in Table 2. We assume the slight deviation would not significantly affect system performance.

Table 1
Inputs for the simulations.

Plasma gasification	
	Feces
C (wt. %)	42.96
H (wt. %)	6.3
O (wt. %)	By difference
N (wt. %)	2.36
S (wt. %)	0.089[a]
Ash (wt. %)	12.5
HHV (dry, kJ kg^{-1})	18,216
Gas cleaning	
Pressure drop (Pa)	6000
Temperature change (°C)	Variable
SOFC	
Number of cells	180
Single cell active area (cm^2)	127.8
Resistance (Ωcm^2)	6.5×10^{-5}
Fuel utilization (%)	50–80
Operating temperature (°C)	800
Operating pressure (Pa)	1.033
Pressure drops (Pa)	2000
Electrode off-gas temperature (°C)	820

[a] The average value from the samples in Schouw et al. [14].

5. Results and discussion

5.1. Comparison between the addition of air and steam

Fig. 6 presents the energy system when steam is used to suppress carbon deposition. Different from the power plant with air addition shown in Fig. 5, steam generated with a heat exchanger (No.20) is used. Additionally, another heat exchanger (No.28) is employed to preheat the fuel delivered by pipe No.33 to approximately 700 °C. This preheating is accomplished by the combustor (No.17).

Thermodynamic calculations demonstrate that adding 0.26 gs^{-1} of air (ambient temperature and pressure) or 0.07 gs^{-1} of steam (ambient pressure and 100 °C) are respectively required for the addition of air and steam to thermodynamically suppress carbon deposition. Both approaches sacrifice system performance but affect system performance differently, as can be seen in Fig. 7.

Compared with steam addition, the net electrical efficiency is approximately 3% higher for air addition. Such a difference is raised because of 16% less fuel being utilized (50% against 66%) for the

Table 2
Gasification results comparison.

	Present model	Experiment [8]	Modeling [8]
H_2	23.0	28.0	24.7
CO	26.8	23.6	25.6
CO_2	9.1	9.3	9.01
Ar	0.59	0.46	0.48
N_2	40.2	38.2	40.1
Power consumed (kW kg^{-1})	2.11	2.16	–
Syngas LHV (kW kg^{-1})	12.2	13.5	13.5

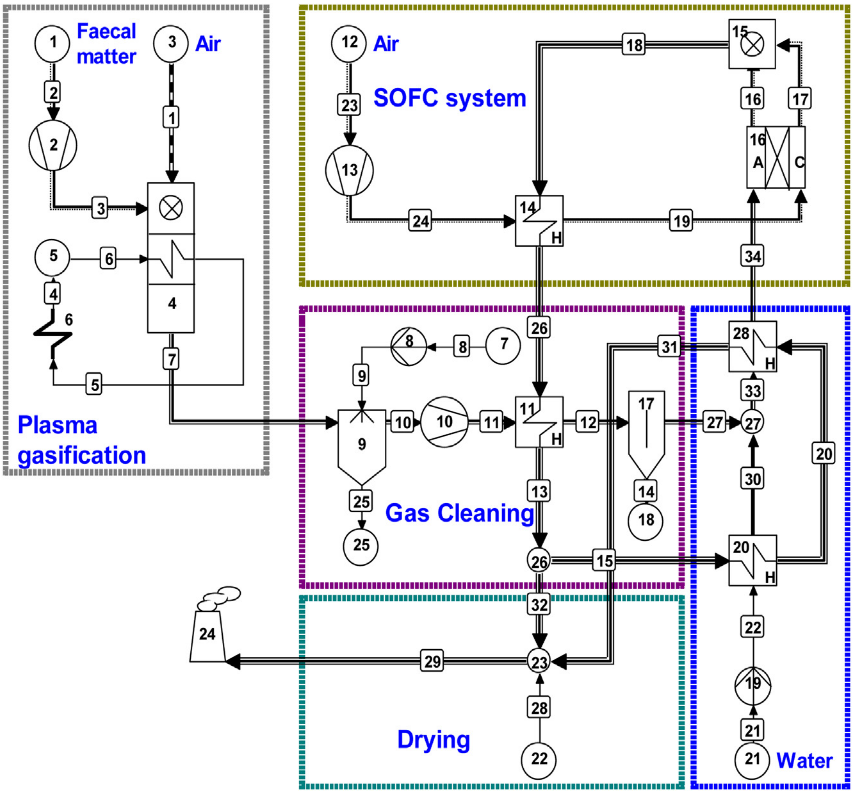

Fig. 6. The energy system using steam for suppressing carbon deposition.

former, which requires more fuel to be combusted in the afterburner in order to provide more heat for steam generation and drying, and thus generating less electricity. As much less fuel is electrochemically oxidized, the air flow rate also decreases for the case of steam addition. As a consequence, the power consumed by auxiliary components also slightly decrease for steam addition. Carbon deposition can be avoided with both approaches but also require extra components (steam generator/heat exchanger, or reactor). Although the two cases are likely to become self-sustained in both electricity and heat, the net electricity generated is slightly higher for the case of adding air. Therefore, adding air is likely to be superior and is used in the following studies. In the following sections, the amount of air added is controlled in such a way that it is able to firstly suppress carbon deposition and secondly to obtain a certain outlet temperature (between ~700 and 750 °C).

5.2. The effects of drying

For the case without drying, when feeding 0.8 gs^{-1} of pre-dried faecal matter and 0.84 gs^{-1} of air to the gasification furnace, by-products from the plasma gasification process accounts for approximately 13 wt.% of the total mass inputs. The clean syngas as fuel for the SOFC is able to generate 3.5 kW electricity under the conditions applied, which exceeds the electricity required (2.27 kW) for the plasma gasification. The surplus electricity equals to 12% of the chemical energy input of the faecal matter. Approximately 4 kW heat can be recovered, and this brings the total CHP efficiency up to 57%. However, when including the drying, the fuel utilization is decreased from 80% to 66% generating heat; consequently, the net electrical efficiency decreases to ~6% and the total CHP efficiency decreases to 5% as well. Nevertheless, the entire system is self-sustained in both electricity and heat. The exergy performance for the case without drying is also much better than that with the drying case, as summarized in Table 3.

Fig. 8 presents the energy flow diagram of the power plant with drying included. It is clear that AC electricity generated, approximately 3 kW, can overcome the 2.3 kW electricity consumed by the plasmatron. By decreasing the fuel utilization of the SOFC system, the flue gas can provide sufficient heat for preheating fuel and air and drying 2 gs^{-1} water vapor.

As seen in Fig. 9, the plasma gasification accounts for 25%, being the largest exergy destruction among the subsections selected. The drying occupies 13% of the total exergy losses and the gas cleaning system takes 10%. The CPOX (catalytic partial oxidation) and the

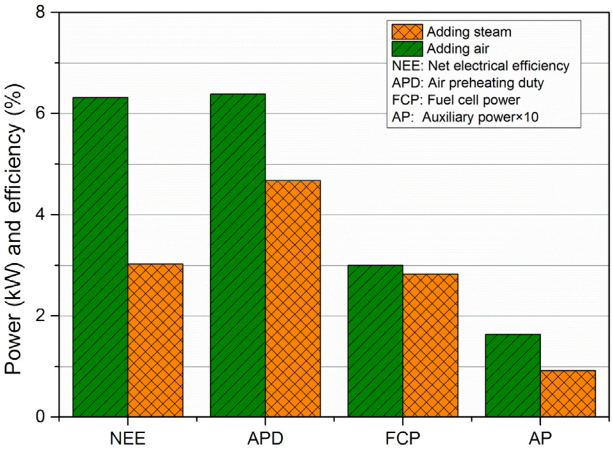

Fig. 7. System comparison between the addition of air and steam.

Table 3
System performance without and with drying.

	Without drying calculated		With drying calculated	
	Energy	Exergy	Energy	Exergy
Biomass input (kW)	8.84	10.57	8.84	10.57
Electricity for microwave (kW)	2.27	2.27	2.27	2.27
Auxiliary power consumed (kW)	0.18	0.18	0.16	0.16
Electricity generated (kW)	3.48	3.48	2.99	2.99
Heat recovered (kW)	3.98	1.59	0.0	0.0
Gross electrical efficiency (%)	39.38	32.9	33.80	28.27
Net electrical efficiency (%)	11.68	9.72	6.32	5.29
Heat efficiency (%)	44.99	15.07	0.0	0.0
CHP efficiency (%)	56.67	24.79	6.32	5.29

SOFC stack occupy relatively smaller exergy losses, which are less than 3%. These main losses result in a total net exergy efficiency of 5.3%.

5.3. *The effects of moisture content*

Fig. 10 compares the energy production, consumption and the electrical efficiency in the case faecal matter is fed with a moisture content of 30% and 40% by weight.

The electricity for the plasmatron decreases when the moisture content raises. This is true as less usable fuel is available, which also reduces the amount of electricity generated. Preserving fuel utilization at 80% shows only a part of drying can be processed, and hence in both cases the fuel utilization is decreased for generating more heat. The power consumed by the plasmatron decreases when raising the moisture content, in fact more electricity is generated and hence higher net electrical efficiency for the lower moisture content.

5.4. *The effects of air to fuel ratio*

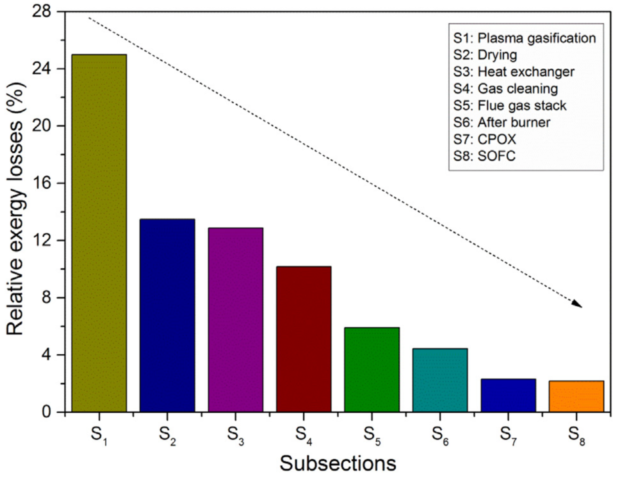

Fig. 9. Relative exergy loss of subsections for the power plant with drying.

Fig. 11 presents the effects of OTFR (oxidant-to-fuel ratio)(kg kg^{-1}) on power generation and consumption (the fuel flow rate is remained). It can be seen that when increasing the air mass flow rate, less power is required for the plasmatron (represented by EFP (electricity for plasmatron)) because more biomass is likely to be oxidized, providing more heat for the gasification furnace and hence requires less electricity for the plasmatron. The electrical power generated also becomes less because less fuel is gasified. Among the three cases, the net electricity (power generated minus the power consumed) and hence the net electrical efficiency are higher for a larger OTFR. This is mainly because the electricity consumed by the plasmatron is reduced more for the larger OTFR. However, excessively raising the oxidant flow rate may result in the presence of oxygen in the syngas, which is highly undesirable for SOFC anodes.

The LHV of the syngas generated decreases against the increase of the OTFR. This is mainly because of the less combustible gases generated for the case of higher OTFR, albeit the mass flow rate of raw syngas slightly increases. The CPOX aforementioned requires a higher air flow rate for a lower OTFR, which further allows less fuel being reduced (70%, 66% and 64% respectively used) to provide more heat for a complete drying. This explains the difference plotted in Fig. 12.

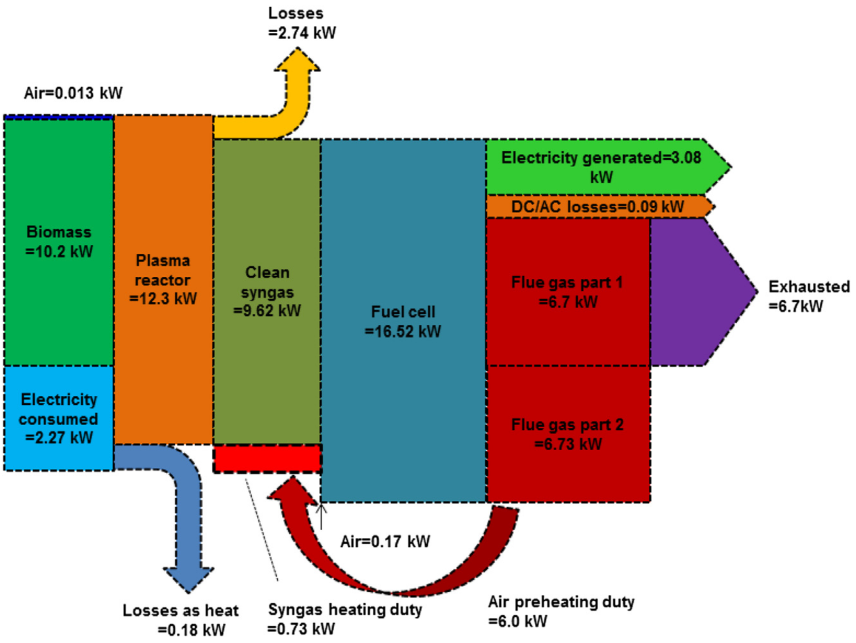

Fig. 8. Energy flow for the power plant with drying (based on HHV).

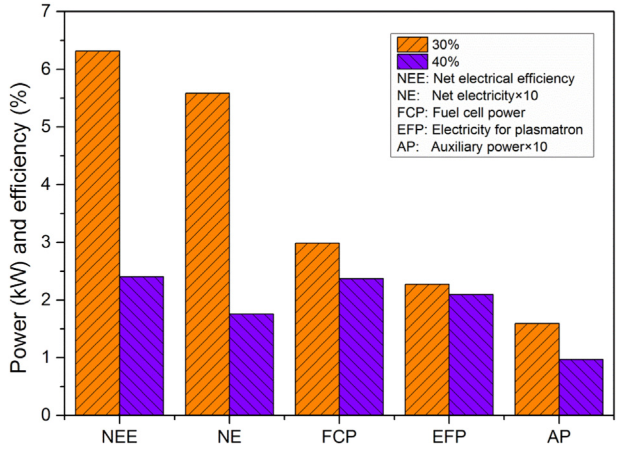

Fig. 10. The effects of water content on system performance.

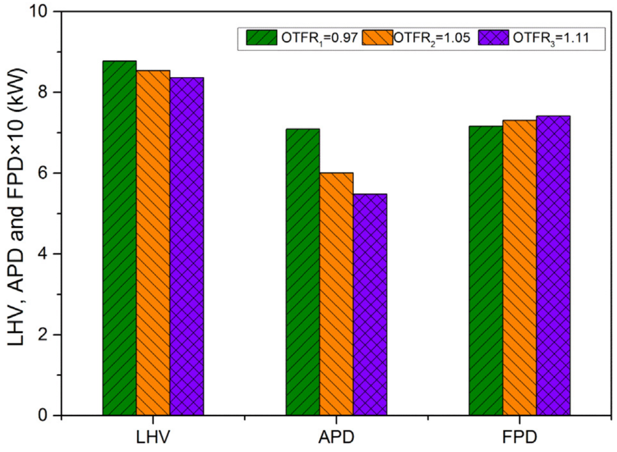

Fig. 12. The effects of oxidant-to-fuel ratio on LHV, APD (air preheating duty) and FPD (fuel preheating duty).

6. Conclusion and outlook

This work presents the development of a power plant for upgrading human waste to power by the employment of plasma gasification and SOFC technologies. We studied the effects of various operating parameters including the gas processing approach for carbon deposition suppression, implementation of drying or not, moisture content of biomass, and air to fuel ratio, on system self-sustainability in electricity and heat. It is found that the use of air addition, lower moisture content, and larger oxidant-to-fuel ratio favors the production of net electricity, and the system self-sustainability is achievable by the adjustment of fuel utilization. However, it should be noted that the surplus electricity is not substantial and other factors such as gas cleaning technology and heat losses, also can potentially affect the system self-sustainability, which shall be investigated in detail in the future. Furthermore, the design, frequency and configuration of the plasmatron can strongly affect the conversion efficiency of power-to-plasma, which further affects the system self-sustainability, and thus need to be studied in the future. Additionally, an efficient drying process also impacts the entire system self-sustainability. Detailed measurements on the power plant are needed to further evaluate system self-sustainability or to minimize the external sources input for the power plant. The results presented are to be further validated by measurements.

The economic and technical feasibility of the entire system addressed is yet to be improved. For example, current SOFC technology is still quite expensive and its long-term performance is yet to be characterized. Thus, continuous efforts in reducing the cost of raw materials and fabrication processes, prolonging cell service life and performance, and understanding system performance from detailed modeling and broad-based operating experience.

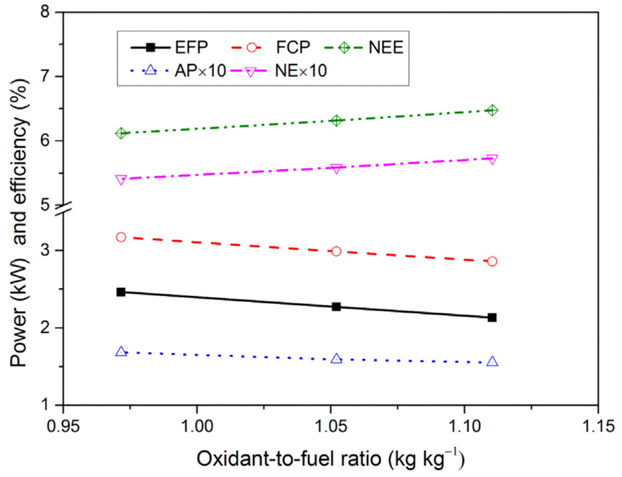

Fig. 11. The effects of oxidant-to-fuel ratio on power generation and consumption.

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References

[1] Hong YC, Lee SJ, Shin DH, Kim YJ, Lee BJ, Cho SY, et al. Syngas production from gasification of brown coal in a microwave torch plasma. Energy 2012;47(1):36–40.
[2] Wang MJ, Huang YF, Chiueh PT, Kuan WH, Lo SL. Microwave-induced torrefaction of rice husk and sugarcane residues. Energy 2012;37(1):177–84.
[3] Lupa CJ, Wylie SR, Shaw A, Al-Shamma'a A, Sweetman AJ, Herbert BMJ. Gas evolution and syngas heating value from advanced thermal treatment of waste using microwave-induced plasma. Renew Energy 2013;50:1065–72.
[4] Uhm HS, Hong YC, Shin DH. Microwave plasma torch and its applications, http://event.cwi.nl/icpig05/cd/D:/pdf/00-216.pdf.
[5] Ray R, Taylor R, Chapman C. The deployment of an advanced gasification technology in the treatment of household and other waste streams. Process Saf Environ Protect 2012;90(3):213–20.
[6] Yoon SJ, Lee JG. Hydrogen-rich syngas production through coal and charcoal gasification using microwave steam and air plasma torch. Int J Hydrogen Energy 2012;37(22):17093–100.
[7] http://www.sairem.com/plasma-sources-56.html.
[8] Rutberg PG, Bratsev AN, Kuznetsov VA, Popov VE, Ufimtsev AA, Shtengel SV. On efficiency of plasma gasification of wood residues. Biomass Bioenergy 2011;35(1):495–504.
[9] Aravind PV, de Jong W. Evaluation of high temperature gas cleaning options for biomass gasification product gas for Solid Oxide Fuel Cells. Prog Energy Combust Sci 2012;38(6):737–64.
[10] Aravind PV. Studies on high efficiency energy systems based on biomass gasification and solid oxide fuel cells with Ni/GDC anodes [PhD thesis]. The Netherlands: Delft University of Technology; 2007.
[11] Aravind PV, Woudstra T, Woudstra N, Spliethoff H. Thermodynamic evaluation of small-scale systems with biomass gasifiers, solid oxide fuel cells with Ni/GDC anodes and gas turbines. J Power Sources 2009;190(2):461–75.
[12] Cycle-tempo. TU Delft; 2006.www.cycle-tempo.nl.
[13] Minutillo M, Perna A, Di Bona D. Modelling and performance analysis of an integrated plasma gasification combined cycle (IPGCC) power plant. Energy Convers Manag 2009;50(11):2837–42.
[14] Schouw NL, Danteravanich S, Mosbaek H, Tjell JC. Composition of human excreta – a case study from Southern Thailand. Sci Total Environ 2002;286(1–3):155–66.
[15] Liu M, Aravind PV, Woudstra T, Cobas VRM, Verkooijen AHM. Development of an integrated gasifier-solid oxide fuel cell test system: a detailed system study. J Power Sources 2011;196(17):7277–89.